Intrinsic tunneling spectroscopy in small Bi2212 mesas

Vladimir Krasnov[1,2], August Yurgens[1,3], Dag Winkler[4,1] and Per Delsing[1]

[1] *MINA, Chalmers University of Technology, S41296, Göteborg, Sweden*
[2] *Institute of Solid state Physics, 142432 Chernogolovka, Russia*
[3] *P.L.Kapitsa Institute, 117334 Moscow, Russia*
[4] *IMEGO Institute, Aschebergsgatan 46, S41133, Göteborg, Sweden*

Tunneling spectroscopy of high-T_c superconductors (HTSC) provides an important information about quasiparticle density of states (DOS), which is crucial for understanding HTSC mechanism. Surface tunneling experiments [1, 2] showed, that besides the superconducting gap in the DOS, Δ, there is a structure usually referred to as the "pseudo-gap", which exists well above T_c. Both the behaviour of the superconducting gap and it's correlation with the pseudo-gap are still a matter of controversy[1, 2].

To avoid drawbacks of surface tunneling experiments, such as dependence on the surface deterioration, surface states and undefined geometry[2], we used "intrinsic" tunneling spectroscopy. HTSC single crystals can be considered as stacks of atomic scale intrinsic Josephson junctions (IJJ's). Using microfabrication, it is possible to make small HTSC mesa structures with a well defined geometry[3]. Moreover, IJJ's far from the sample surface can be measured, and deterioration of the sample surface becomes less important. Current-voltage characteristics (IVC's) of mesas exhibiting tunnel junction behavior and can be used for studying DOS[4]. On the other hand, intrinsic tunneling spectroscopy can suffer from ohmic heating of the IJJ's and steps (defects) on the surface of the crystal.

In this paper we present experimental data for small area $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) mesas containing few IJJ's. By decreasing the mesa area, S, we minimize both the effect of overheating and the probability of defects in the mesa. Mesas with dimensions from 2 to 20 μm were fabricated simultaneously on top of Bi2212 single crystals. First a long and narrow mesa was fabricated using photolithography and chemical etching. Next, insulating CaF_2 layer was deposited and lift-off was used to make an opening. Finally, Ag film was deposited and electrodes were formed on top of the initial mesa by photolithography and Ar-ion etching. After etching, mesas beneath Ag electrodes remain.

In Fig.1, normalized IVC's of three mesas at T=4.2K and T=150 K are shown. The vertical axis represents the current density, $J = I/S$, and the horizontal axis shows the voltage per junction, V/N. IVC's for different samples are plotted by different colours. Parameters of the mesas are listed in Table 1. From Fig.1 it is seen, that the normalized IVC's merge quite well into one curve. This indicates good reproducibility of the fabrication procedure. The c-axis normal resistivity was,

$\rho_N = R_N S/Ns = 44 \pm 2.0$ Ωcm, where $s = 15.5 \mathring{A}$ is the spacing periodicity of IJJ's and R_N is the resistance at large bias current and $T_c \simeq 93$ K.

Table 1:	mesa	S (μm^2)	N	$R_N(\Omega)$
	S251b	6×6	12	229.9
	S255b	5.5×6	12	256.4
	S211b	4×7.5	12	272.5
	S216b	4×20	10	87

From Fig.1 it is seen that IVC's exhibit clear tunnel junction behavior: (i) At low bias, multiple quasiparticle branches are seen, representing one-by-one switching of IJJ's into the resistive state[3, 4]. The number of IJJ's in the mesa was obtained by counting those branches. (ii) At intermediate currents there is a pronounced knee in IVC's, representing the sum-gap voltage, $V_g = 2\Delta/e$. (iii) At high currents, there is a well defined normal resistance branch, R_N. As seen from Fig.1, R_N is almost temperature independent, as may be expected for a tunnel resistance. In contrast, the zero bias resistance, $R(0)$, increases sharply with decreasing T, as shown in inset b).

Inset a) in Fig.1 shows temperature dependence of the gap voltage, V_g, and the maximum spacing between multiple quasiparticle branches, ΔV, for four mesas on two diffrent chips. Solid and open symbols represent branches for $V > 0$ and $V < 0$, respectively. ΔV was determined at the "maximum critical current", at which the last IJJ switches to the resistive state, e.g. in Fig.1 that would correspond to $J \simeq 1.3 \times 10^3$ A/cm^2. This current is fluctuating from run to run, therefore, causing an uncertainty in determination of ΔV. From the inset a) it is seen, that ΔV is approximately two times less than V_g. This is simply due to the fact that all the IJJ's switch to the resistive state before they reach the gap voltage, see Fig.1. However, it is seen that the temperature dependence of ΔV reflects that for V_g. The observed V_g correspond to $\Delta \simeq 32$ meV at T=4.2 K, in agreement with [2].

The IVC's in Fig.1 suggest that there is no significant heating effect in our mesas. Indeed, overheating should cause the reduction of V_g. Instead, we observed that the normalized IVC's merge into a single curve with identical V_g, despite a considerable difference in the dissipated power, $P \propto S$. Moreover, we have checked that the voltages of the quasiparticle branches scale with their number, $V_n \simeq \frac{n}{N} V_N$, where V_N is the top branch, with all IJJ's in the resistive state. Thus, switching of additional IJJ's does not cause visible overheating of the
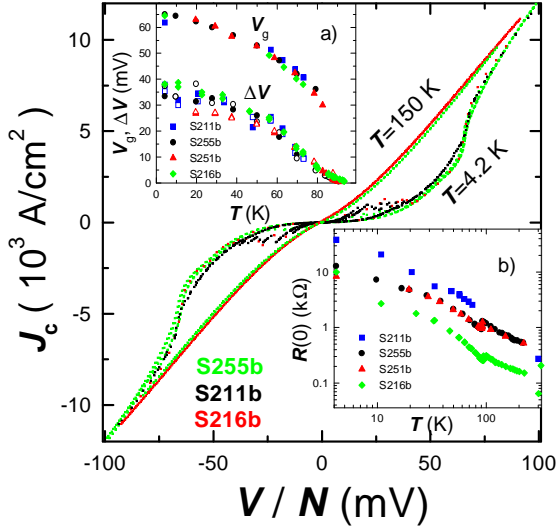
Figure 1: J vs. V/N curves for three mesas at T=4.2K and T=150 K. Inset a) shows temperature dependencies of the gap voltage, V_g, and the voltage separation of multiple quasiparticle branches, ΔV. Inset b) shows temperature dependencies of the zero-bias resistance.

Figure 2: Conductance at different temperatures for $6 \times 6 \ \mu m^2$ mesa.

mesa. On the other hand, we did observe a strong overheating for even smaller mesas ($2\times4 \ \mu m^2$), containing larger number of IJJ's (~ 100), so that a clear back-banding was seen at large currents, and significantly lower V_g was obtained, similar to that in Refs.[3, 5]. Therefore, a small number of IJJ's in the mesa decreases the risk of overheating.

In Fig.2, the conductance at different temperatures is shown for one of the samples. The sharp peak at V_g and the depletion of conductance at $|V| < V_g$ is seen at low T, representing the superconducting gap in the DOS. The suppression of DOS below the gap results in strong temperature dependence of $R(0)$, see inset b) in Fig.1. With increasing temperature, the peak at V_g shifts to lower voltages and decreases in magnitude. At $T \sim 80$ K, the peak is smeared out completely and only smooth depletion of the conductance remains at V=0. With the further increase of T, this depletion gradually decreases, but is still visible even at room temperature, representing the pseudo-gap in DOS. In agreement with the surface tunneling experiments[1, 2], there is almost no changes in the conductance at T_c, which implies that the pseudo-gap coexists with the superconductivity.

There is a crucial difference between our, "intrinsic", and the surface tunneling experiments[1, 2], which allows us to distinguish the superconducting gap from the pseudo gap. The difference is in existence of multiple quasiparticle branches in IVC's, see Fig.1. Therefore, we have an additional quantity, the spacing between the quasiparticle branches, ΔV, which can be used for estimation of Δ. Even though the peak in conductance is smeared out at $T >$80 K, the quasiparticle branches in the

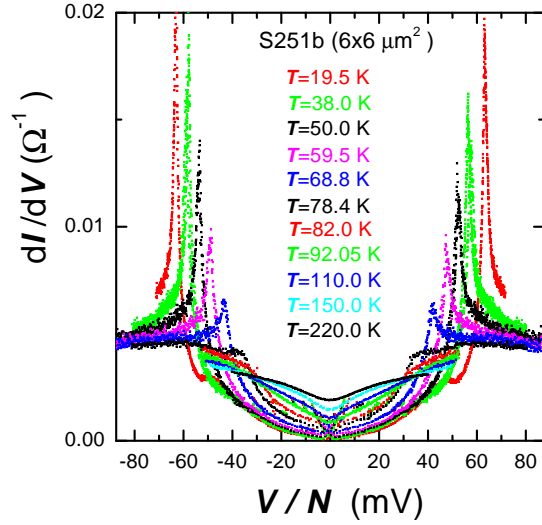IVC's remain well defined up to T_c. The ΔV continuously decreases with increasing T and vanishes exactly at T_c, as shown in inset a) in Fig.1.

This brings us to conclusion that the superconducting gap does close at T_c, in contrast to the statement of Ref.[1]. On the other hand, the pseudo gap is almost independent of T, in agreement with [1, 2]. The pseudo gap can exist well above T_c and, probably, can coexist with the superconducting gap even at $T < T_c$, see Fig.2. We can not conclude that the superconducting gap is developed from the pseudo gap nor that they are competing with each other. From our experiment, it seems more natural to assume that those two gaps are independent or only weakly dependent, despite having the same order of magnitude. In Ref. [6] possible scenarios of the pseudo gap were reviewed. One of the possible mechanisms is due to Coulomb charging effect in IJJ's. Some experimental evidence for that was obtained in [5]. For the smallest mesas, we have also seen certain features, such as a complete suppression of the critical current and an offset voltage in IVC's, which may be explained in terms of the Coulomb charging effect. However, further study is necessary before making a decisive conclusion about the origin of the pseudo-gap.

References

[1] Ch.Renner, et al, Phys.Rev.Lett. **80**(1998) 149

[2] Y.DeWilde, et al, Phys.Rev.Lett. **80**(1998) 153

[3] A.Yurgens,et al, Physica C **235-240**(1994)3269

[4] M.Itoh, et al, Phys.Rev.B **55** (1997) R12001

[5] Yu.I.Latyshev, et al, JETP Letters **69**(1999) 84

[6] J.Halbritter, Proc.SPIE **3480** (1998) 222